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Optimization of Location of Injection Wells in an Open Geothermal System

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Abstract. A geothermal open loop system consisting of one production well and several injection wells is considered. The production well serves to raise hot water from a geothermal underground reservoir, which can be used for building heating or for other purposes. As a result, the water is cooled and then pumped through injection wells back into the geothermal reservoir. The cooled water begins to be filtered in the reservoir in the direction of the production well. A mathematical model describing the distribution of a cold water front in such a system is presented. A software package has been developed that makes it possible to evaluate the efficiency of the location of injection wells in a geothermal reservoir in order to increase the operating time of such a system, since the operation of the geothermal system life is over as soon as the cold water front reaches the production well.

INTRODUCTION

Today, in view of the depletion of non-renewable energy sources, the development and practical use of geothermal resources, which are available in many countries, is becoming relevant. In Russia perspective geothermal resources are located in the Central, North-West, Urals, South and North Caucasus, West Siberian, Krasnoyarsk regions, Chukotka, Kamchatka and Sakhalin. Geothermal energy is a type of renewable energy that encourages conservation of natural resources. Geothermal stations are in exploitation also in North Caucasus, Stavropol and Krasnodar regions. For these purposes up to 30 bln. m³ of geothermal water is produced with temperature 80°–110°C.

According to the U.S. Environmental Protection Agency, geothermal systems save homeowners 30–70% in heating costs, and 20–50% in cooling costs, compared to conventional systems [1]. There are two main types of geothermal systems: open loop and closed loop systems. The closed loop system deals with a fluid circulating in pipes through the ground and back through the heat pump. The open loop system uses a water well pump to deliver the water and return the used water back to the aquifer. We will consider a geothermal cyclic open loop system (GCS), consisting of several wells: production well, which delivers hot water from the deep aquifer, and injection wells, which pump the waste cold water into the productive layer. Now, the geothermal system includes a reservoir (aquifer) of geothermal waters throughout the whole service life, that is a geological component with changing characteristics during operation. An important task is to correctly determine the basic parameters for the design of a geothermal system at the initial stage of the project with using the known characteristics of the geothermal reservoir and the forecast of their change.

A significant part of Russia is characterized by the presence of natural low and medium temperature (50°–150°C) reservoirs located at depths from 200 to 3000 meters. The injection of waste geothermal water into production reservoirs is an effective method of maintaining the pressure and filling of the aquifer with restorable temperature due to earth heat, and, in addition, protecting the environment from the harmful effects of highly mineralized thermal waters.

Optimization in the design of a geothermal station is associated, in particular, with locations of production and injection wells and the pressure values in these wells. The time of operation of the geothermal system depends on the locations of the well bottoms in the productive layer: if the bottom of the injection well is close to the bottom of the production well and there is a large pressure drop between these wells, then cold water from the injection well will flow into the production well and the geothermal system in this case will not be exploited.

In this paper, we continue the research of geothermal systems, which were carried out in [2, 3, 4, 5]. The focus is on the study of geothermal systems consisting of several wells. Unlike the papers [6, 7] we will consider a geothermal system consisting of one production well and several injection wells.

MATHEMATICAL MODEL OF COLD WATER DISTRIBUTION IN THE PRODUCTIVE LAYER

Let consider a mathematical model of an open geothermal loop system for our case Fig. 1, when there is one production well Ω_1 with the water temperature $T_1(t)$ and several injection wells Ω_i , $i \geq 2$ with the water temperature $T_i(t)$, ($T_1(0) > T_i(0)$).

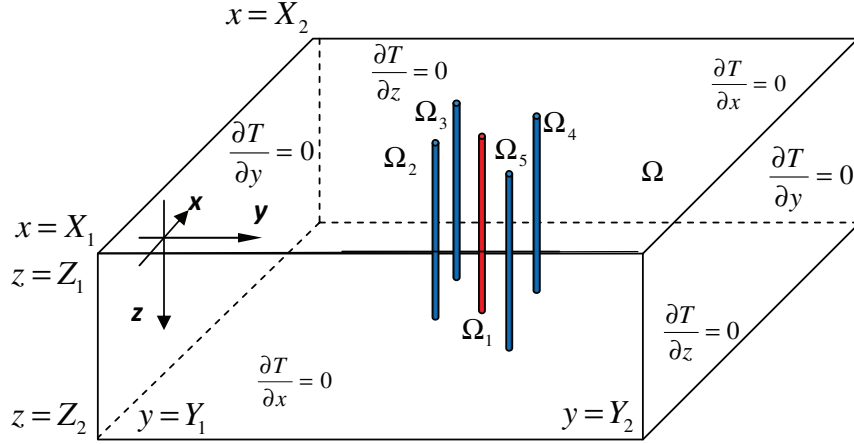


FIGURE 1. A basic scheme of simulated area.

In a general case, fluid motion in a geothermal aquifer Ω is described by the Navier–Stokes equations. For the equations of underground hydrodynamics describing the motion of water in a porous soil [8] it is assumed that the fluid velocity components $V = (u, v, w)$ and the derivatives with respect to the coordinates x, y, z are small. These equations are reduced to the system

$$\begin{cases} \frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{g\sigma u}{k}, \\ \frac{\partial v}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial y} - \frac{g\sigma v}{k}, \\ \frac{\partial w}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{g\sigma w}{k} - g. \end{cases} \quad (1)$$

Here k and σ are average filtration coefficient and porosity in the aquifer, g is the standard gravity, $p = p(t, x, y, z)$ is the pressure.

We assume that at the initial time moment the fluid in the productive layer is at rest, i.e.

$$u(0, x, y, z) = v(0, x, y, z) = w(0, x, y, z) = 0. \quad (2)$$

System (1) is a consequence of the Navier–Stokes equations under assumption, that the quadratic terms are not taken into account in view of the smallness. The validity of such a linearization is discussed and justified in [8].

We will assume that the aquifer Ω (Fig. 1) is located between two unpenetrable layers, bounded by the parallel planes $z = Z_1$ and $z = Z_2$. On these surfaces for pressure we set the boundary conditions

$$\left. \frac{\partial p}{\partial z} \right|_{z=Z_j} = 0, \quad j = 1, 2. \quad (3)$$

Similar conditions are given on the lateral surfaces of the computational domain

$$\left. \frac{\partial p}{\partial x} \right|_{x=X_j} = \left. \frac{\partial p}{\partial y} \right|_{y=Y_j} = 0, \quad j = 1, 2. \quad (4)$$

Denote the cylindrical surface of the production well with radius r_1 by γ_1 and m cylindrical surfaces of the injection wells with radius r_i by γ_i and $\gamma_i, i = \overline{2, m}$, respectively ($Z_1 < z < Z_2$). On these surfaces, we set the pressures

$$P(t, x, y, z)|_{\gamma_1} = P_1 - \rho g z, \quad P(t, x, y, z)|_{\gamma_i} = P_i - \rho g z, \quad i = \overline{2, m}. \quad (5)$$

In Ω excluding Ω_1 and $\Omega_i, i = \overline{2, m}$ the hydrostatic pressure, the pressure of the liquid column at a depth of z is considered as an initial pressure $P(0, x, y, z)$

$$P(0, x, y, z) = -\rho g z. \quad (6)$$

To determine the pressure in Ω we consider the piezoconductivity equation [9, 10]

$$\frac{\partial p}{\partial t} = \omega \Delta p. \quad (7)$$

For equation (7) the boundary and initial conditions (3)–(6) are given. Equation (7) is solved together with system (1) and initial condition (2). A pressure distribution in the aquifer Ω is obtained as a solution of the problem (1)–(7) and used to get the velocity field (u, v, w) .

Let $T = T(t, x, y, z)$ be a temperature distribution in Ω at the time moment t . The heat transfer in Ω will be carried out in two ways: convective and diffusion. Then the equation for the temperature in the aquifer will have the form [2]

$$\frac{\partial T}{\partial t} + b \left(\frac{\partial T}{\partial x} u + \frac{\partial T}{\partial y} v + \frac{\partial T}{\partial z} w \right) = \lambda_0 \Delta T, \quad (8)$$

which have be considered together with the equations for the velocity components (u, v, w) of the fluid filtration in a porous soil, and where $b = \frac{\sigma \rho c_f}{\rho_0 c_0 (1 - \sigma) + \rho c_f \sigma}$, $\lambda_0 = \frac{\kappa_0}{\rho_0 c_0 (1 - \sigma) + \rho c_f \sigma}$, ρ_0 and ρ_f are density of aquifer soil and of water, c_0 and c_f are specific heats of aquifer soil and of water, κ_0 is thermal conductivity coefficient of soil, σ is porosity. The aquifer has an initial temperature

$$T(0, x, y, z) = T_0(x, y, z). \quad (9)$$

In injection wells Ω_i temperature is set as “cold water” with temperature T_i , which returns from production well after using. At the surface γ_i of Ω_i we will set the temperature of injected water

$$T(t, x, y, z)|_{\gamma_i} = T_i, \quad i = \overline{2, m}. \quad (10)$$

At the initial time on the surface γ_1 the temperature is equal to the temperature (9). Subsequently, during calculations, the temperature at the producing well $T_1(t)$ will vary due to the fact that the injected water has a lower temperature $T_i, i = \overline{2, m}$. On the planes $z = Z_j$ we set a geothermal heat flux

$$\left. \frac{\partial T}{\partial z} \right|_{z=Z_j} = \Gamma_j, \quad j = 1, 2. \quad (11)$$

On the lateral boundaries we will use zero heat flux conditions

$$\left. \frac{\partial T}{\partial x} \right|_{x=X_j} = \left. \frac{\partial T}{\partial y} \right|_{y=Y_j} = 0, \quad j = 1, 2. \quad (12)$$

Thus, for the temperature $T(t, x, y, z)$ described by equation (8), all the necessary initial and boundary conditions (9)–(12) are given.

NUMERICAL SOLUTION

To solve the equations (1)–(7) for temperature and pressure in aquifer we used an implicit additive finite difference method with splitting by the spatial variables in Ω [2, 3, 4, 6, 7]. We construct an orthogonal grid, uniform, or condensing near the ground surface and to the surfaces of injection and production wells. An additive finite difference method is based on an approach of works of A.A.Samarskii and P.N.Vabishevich [11]. The original equation for each spatial direction is approximated by an implicit central-difference scheme and a three-point sweep method to solve system of linear differential algebraic equations is used. This approach was successively used for the problems of describing a thermal trace from underground pipeline taking into account filtration and evaporation of fluid from soil surface [12]. A qualitative comparison of the numerical results was carried out, for example, with the work of French researchers for the geothermal cyclic system in Paris district [13]). For more accurate quantitative comparisons of solutions, additional data are needed. The accuracy of the calculations was also controlled by calculations on a sequence of computational grids.

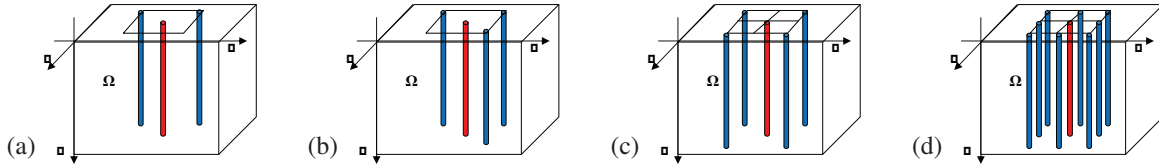


FIGURE 2. The considered well systems: the injection and producing wells are blue and red, respectively.

TABLE 1. Cyclic geothermal open loop systems with different injection wells number and the pressure values.

Number of wells of GCS	Pressure in producing well	The number of injection wells and pressure	Cases and results of simulations
2 wells	1200 kPa	1 1200 kPa	Fig.5a
3 wells	1200 kPa	2 600 kPa	Fig.2a-4a Fig.5b
4 wells	1200 kPa	3 400 kPa	Fig.2b-4b Fig.5c
5 wells	1200 kPa	4 300 kPa	Fig.2c-4c Fig.5d, blue and red lines
9 wells	1200 kPa	8 150 kPa	Fig.2d-4d Fig.5d, green line

RESULTS OF NUMERICAL SIMULATION OF GEOTHERMAL SYSTEMS

Let consider a porous soil layer as a computational area. The layer sizes are 6000m-6000m-50m. Thermal parameters of the aquifer are the following: thermal conductivity is 2,00 [W/(mK)], density is 1000,0 [kg/m³], specific heat is 4,18 [J/(kg K)], volumetric heat is 2150,0 [J/(m³K)], filtration velocity is $1,7 \cdot 10^{-5}$ [m/s], porosity is 0,241. Temperature in aquifer is 95°C, the temperature of injected water is 55°C. There are several production wells in a square area with the

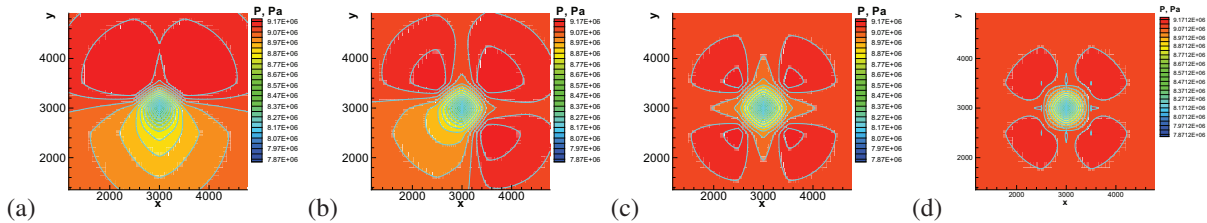


FIGURE 3. Pressure fields in a horizontal plane.

edge of 1000 m. Radius of the wells is 0,012m. Five variants (Table 1) of the system in a rectangular net are considered

with the distance between the producing and injection wells of 500 m and 700 m, the position are presented in Fig. 2. In the figures the positions of injection and producing wells are denoted by blue and red colors, respectively. The position of producing well is in the center of the area.

The pressure will be proposed as 1200 kPa in the producing well and the pressure will be distributed between the injection wells. In Table 1 the variants of considered systems and the pressure values are presented.

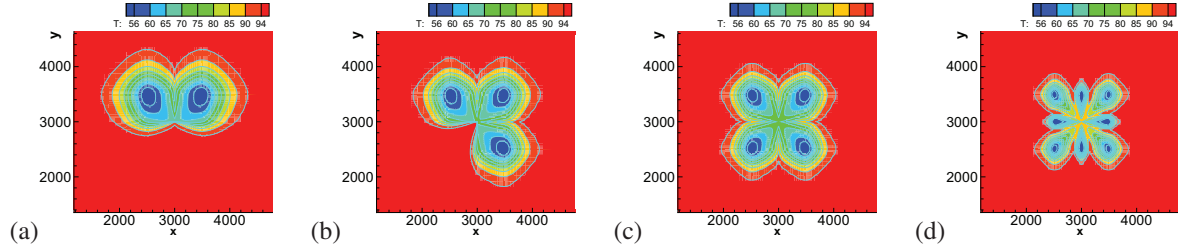


FIGURE 4. Thermal field for 25 years of simulations in a horizontal plane.

In Fig. 3 the pressure fields in a horizontal plane are shown. The simulated water filtration process is suggested to be steady-state and be valid during all the time of the system exploitation. The isobar lines show the zones of hot water collection and allow to estimate the surface water intake regions.

In Fig. 4 the thermal fields are shown for 25 years of simulations. The cold spots around the injection wells depends on the pressure in the wells. For the case of three wells system the cold water injection is more intensive.

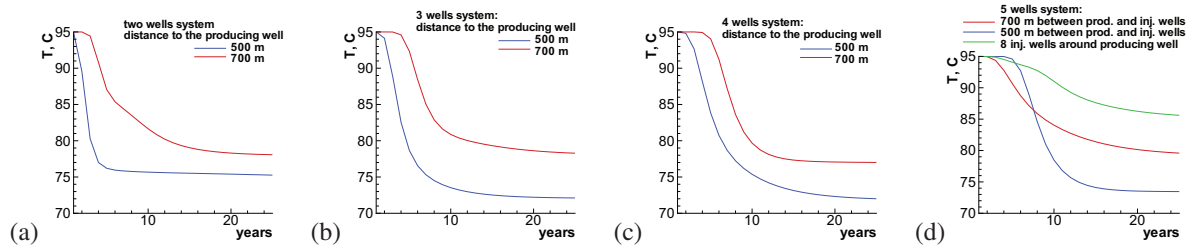


FIGURE 5. Temperature in the production well during 25 years.

In Fig. 5 the temperature in producing well are presented for 25 years of exploitation. The variants with two (Fig.5a), three (Fig.5b), and four wells (Fig.5c) are similar and the resulting temperature depends on the distance between the producing and injection well. But when the system of 9 wells (Fig.2d and 5d, green line) is considered in compare with the system of 5 wells (Fig.2c and 5d, blue and red lines) it turns out that the lower pressure of cold water in the injection well is more effective in view to the water reheating and filtration in the aquifer.

CONCLUSION

For investigation of open loop geothermal systems a mathematical model and numerical algorithm are used. The system consisting of one producing and several injection wells is considered. The simulations include the water filtration in a porous soil and temperature changes in the aquifer due to the waste water injection under the pumps operation. The dynamics of changes in the temperature of hot water in production well depends on various parameters. The main parameters of the system are the distance between the wells in the productive layer and the pressure in the wells. It is observed that waste cold water should be returned into the aquifer with slower pressure and have to be distributed in the area to reheating and renew the thermal energy resource and more effective the cyclic open loop system exploitation.

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